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NONLINEAR BRIDGE FOR MEASURING ELECTROTHERMAL CHARACTERISTICS OF BRIDGEWIRES

Prepared by:
Louis A. Rosenthal*

ABSTRACT: Due to thermal follow a bridgewire will generate a third harmonic voltage drop when passing a sinusoidal current. By measuring the phase lag and amplitude of this harmonic, the thermal time constant and heat loss factor can be determined. An AC bridge is employed to extract the third harmonic voltage and directly measure its phase angle.

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* Professor of Electrical Engineering, Rutgers University and Consultant to the Naval Ordnance Laboratory.

Explosion Dynamics Division
Explosions Research Department
U. S. NAVAL ORDNANCE LABORATORY
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Nonlinear Bridge for Measuring Electrothermal Characteristics of Bridgewires

This report describes the theory, construction, and operation of a new instrument developed to determine the thermal parameters of bridgewire type electro-explosive devices. The new instrument allows much more rapid measurement of the parameters than previously possible, but of even greater significance is the fact that it allows simple measurement on devices having bridgewires of low thermal coefficient of resistivity (for instance, nichrome).

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R. E. ODENING
Captain, USN
Commander

C. J. Aronson

C. J. ARONSON
By direction

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ILLUSTRATIONS

REFERENCES

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INTRODUCTION

The measurement of the electrothermal parameters of a bridgewire and their dependence on the surrounding explosive mixtures in electro-explosive devices (EEDs) can be of value in EED studies. The response to various electrical input waveforms obviously depends on the thermal time constant (τ), the heat capacity (C_p), and the heat loss factor (γ). A simple and convenient thermal model based on a lumped single time constant system follows the power equation:

$$C_p \frac{d\theta}{dt} + \gamma\theta = P(t) \qquad (1)$$

where P(t) is the power-time function and θ is the temperature elevation of the bridgewire. The thermal time constant τ is defined according to $\tau = C_p/\gamma$. Although more complex models can be proposed when necessary, this simple model can explain many of the electrothermal characteristics observed in EEDs. The task is to measure the parameters in a meaningful and reliable manner and apply them in areas such as quality control and design.

The differential equation (1) can be solved for known transient waveforms to obtain the constants[1]*. For example, impulse and step function power waveforms give rise respectively to exponential cooling or heating curves[2] which can be analyzed. It has been verified that a single time constant can provide a reasonable equivalent model for most bridgewires. In order to track temperature variations, the temperature coefficient of resistivity (α) must be known since it is actually a resistance variation which is measured. In cases where α is very small it is difficult to extract temperature variation information from a transient response curve.

As another approach to the measurement of thermal response, dynamic measurements can be made for a sinusoidal power source. If a sinusoidal current is passed through a thermally sensitive element the power dissipated has an average value and a component at a frequency of 2ω, where ω is the current frequency. The cyclic power variation gives rise to a resistance variation (of the same frequency) which lags for positive α systems, the power sinusoid by some angle. This angle of lag is related to the thermal time constant of the unit. In addition a resistance variation at "2ω" when multiplied by the current at "ω" yields a third harmonic voltage at "3ω". The magnitude of the third harmonic (3ω) voltage and its phase angle are clues to the thermal parameters for the bridgewire.

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* References are listed on page iii.

An earlier paper[8] described this harmonic generation principle and suggested a system for tracking the thermal follow as a function of frequency. For example, it appears that the third harmonic will be down by 3 decibels ($1/\sqrt{2}$) where $\tau=1/2\omega$. A variable frequency driving source was required. As a more direct and simpler procedure a single frequency can be used and by measuring the thermal lag, the time constant can be ascertained. A nonlinear bridge is employed for these measurements. Another advantage of the harmonic generation technique lies in the inherent high resolution provided. The presence of a third harmonic can only be a result of thermal follow. Follow being the ability of the bridgewire to thermally track the driving signal. Although the resistance-temperature sensitivity might be small, there will be a third harmonic which cannot be mistaken. The theoretical aspects of the measurement will be described.

THEORY

Consider an electrothermal element passing a current

$$i=I\sin\omega t.$$

The instantaneous power dissipation will be:

$$i^2R=\frac{I^2}{2}R(1-\cos 2\omega t), \tag{2}$$

where i is the instantaneous current and I is the maximum current. Note that there is an average and cyclic component to the power. This ac. or cyclic power variation is:

$$P_{ac}=\frac{I^2}{2}R\cos 2\omega t \tag{2a}$$

where R is the hot resistance due to an average power:

$$P_{av}=\frac{I^2R}{2} \tag{2b}$$

Because of the ac.power variation there is a temperature fluctuation P_{ac}/γ and a resistance fluctuation

$$R_{ac}=\frac{R\alpha P_{ac}}{\gamma} \tag{3}$$

where α is the temperature coefficient of resistance determined at the hot temperature. Note that R_{ac} is a variation of resistance superimposed on the average hot resistance, R, of the EED. The resistance variation can then be described in the time dependent form

$$R_{ac}=\frac{I^2R^2}{2\gamma}\alpha\cos 2\omega t \tag{3a}$$

providing the follow is complete. Actually the R_{ac} variation lags at some angle β and is in phase with $\theta(t)$, the temperature rise-time function. From the basic differential equation the lag angle $\beta=\tan^{-1}2\omega\tau$. The product of the instantaneous current term and the resistance variation term yields the dynamic voltage drop across the element according to

$$\frac{I^2R^2\alpha}{2\gamma}\cos 2\omega t\sin\omega t \qquad (4)$$

If the trignometric term is expanded as

$$\cos 2\omega t\sin\omega t=\frac{\sin n\omega t}{4}+\frac{\sin 3\omega t}{2} \qquad (4a)$$

then a third harmonic voltage amplitude is found as

$$V_3=\frac{I^3R^2\alpha}{4\gamma} \qquad (4b)$$

where V_3 is the maximum third harmonic voltage. Inserting the rms values results in

$$V_{3\,rms}=\frac{I^3_{\,rms}R^2\alpha}{2\gamma} \qquad (4c)$$

This voltage is lagging at the same angle as the resistance follow (β) and falls off with frequency in accordance with

$$1/\sqrt{1+\tan^2\beta}.$$

The instantaneous value of the third harmonic voltage is

$$v_3(t)=\frac{I^3_{\,rms}R^2\alpha}{\sqrt{2}\gamma\sqrt{1+\tan^2\beta}}\sin(3\omega t-\beta) \qquad (5)$$

where $v_3(t)$ signifies the instantaneous third harmonic voltage. This equation describes the fall off in amplitude and the phase lag observed in the harmonic generated as a function of frequency since $\tan\beta=2\omega Cp/\gamma=2\omega\tau$. These equations complement the derivations of reference 3 . Rather than seek the frequency where $\tan\beta=1$ corresponding to a decrease in the third harmonic amplitude by $1/\sqrt{2}$, it is possible to measure the angle of phase lag at a fixed frequency. This can be accomplished by comparing the third harmonic generated with the fundamental current waveform in a Lissajous phase display. By introducing a calibrated phase lag into the current waveshape a zero phase shift display directly yields the value of β. This can be demonstrated by reference to Figure 1a which shows the basic bridge circuit.

A voltage source $V\sin\omega t$ supplies a constant current through the EED (R) under test since R_1 is much larger (100 times) than R. The voltage drop across R contains a fundamental component and a third harmonic. There is a phase shift in the fundamental due to thermal follow as shown in the expansion of equation (4a). All of the fundamental signal in the error voltage can be eliminated by means of C_X and R_X leaving a nearly pure third harmonic. At balance

$$R\cong R_1R_4/R_X$$

neglecting the slight reactance of C_x. The third harmonic can be measured and displayed on an oscilloscope. In addition another signal which is in phase with the current is passed through the lagging phase shift network R_sC_s to provide a reference phase voltage which can be applied to the horizontal deflection system of the oscilloscope. If the fundamental is shifted by 1/3 the amount the third harmonic is shifted due to thermallag, then both waveforms will be in phase for the oscilloscope display. The result is a unique single valued cubic waveform trace

For example if

$$v = A \sin 3\omega t$$

and $$h = B \sin \omega t$$

corresponding to two waveforms starting from zero in phase with amplitudes A and B respectively, the resulting trace can be determined.

Starting with the identity

$$\sin 3\omega t = 3\sin\omega t - 4\sin^3\omega t$$

and substituting the vertical (v) and horizontal (h) deflections indicated

$$v/A = \frac{3h}{B} - \frac{4h^3}{B^3}$$

or $$v = \frac{3Ah}{B} - \frac{4Ah^3}{B^3} \qquad (6)$$

which is the equation of a cubic as sketched in Figure 1b. The amplitudes at pts 1 and 2 must be equal and the figure is symmetrical about the origin. If some fundamental is in the output or if there is a phase shift then the display opens up, as will be shown later.

Since this unique phase display is a result of matching phase lags, the phase shift of the network R_sC_s can be calibrated as $\beta/3$ or directly as β. It can also be calibrated as a time constant since $\tan\beta = 2\omega\tau$. The maximum phase shift required in the R_sC_s network is 30° corresponding to a 90° thermal lag (or no follow). All measurements can be made at a single frequency. The maximum value of R_s required is $X_C/\sqrt{3}$ (for 30° phase lag). Knowing the phase lag and the third harmonic amplitude it is a simple matter to apply the indicated equations for a determination of τ and γ.

THE APPARATUS

A practical circuit is shown in Figure 2. The 60 cps line supplies power to the EED through a 500 ohm power resistor. With

25 volts available it is possible to pass 50 ma through R. If a variable transformer is applied to the input this current can be reduced to any desired safe level. The current is easily measured by replacing R with a 1 ohm precision resistor and measuring the voltage drop across it. The adjacent comparison arm includes a 20 ohm resistor and a 1K to 5K ohm adjustable arm. A 1K Helipot is included in this arm for a fine degree of balance.

At balance $R=10,000/R_x$ and as shown the range of the bridge is 2 to 10 ohms. By reducing R_4 to 10 ohms by means of a paralleled resistor, the range is cut in half. An external capacitance balances out the reactive components of bridge unbalance.

A high quality isolation input transformer raises the error voltage by a factor of 19.25. This transformer is well shielded and offers no phase shift at the frequencies of interest, which for a 60 cps input corresponds to 180 cps. Care must be taken to provide good grounds and negligible pick-up. With a typical drop of 100 mv across the EED, a 1 millivolt error signal, after the transformer, corresponds to a resistance change of 0.05%. For adequate resolution, an oscilloscope of 1 mv/cm sensitivity should be employed.

The phase shift network is designed for 60 cps, to provide a maximum phase shift of 37°. There is a small variation in amplitude with phase shift which merely changes the horizontal amplitude of the phase display. Although the phase shift can be calculated for various values of R_8 it is more convenient to calibrate this network using a commercial phase angle meter or a counter used for time interval measurements. A practical calibration curve is shown in Figure 3 to provide tan β directly. In Figure 4, the tan β data is plotted to yield τ, the time constant, directly based on tan $\beta=2\omega\tau$ where $\omega=377$. Using 60 cps, the line frequency, time constants from 200μs to 20ms can be measured. If a lower frequency power source is available, this measurement can be extended to large time constant units. Some experimental observations and measurements are presented to demonstrate this technique.

RESULTS

If the bridge of Figure 1 is supplied with a variable frequency source, the harmonic generation and phase shift can be investigated as a function of frequency. For a particular bridgewire the curve of third harmonic vs frequency is shown as Figure 5. Complete follow yields 9mv of harmonic across the bridgewire. At 130 cps the third harmonic is down by $1/\sqrt{2}$ and at 225 cps ($\sqrt{3}$x130 cps) it is down by 1/2. The curve follows the response of a single time constant circuit fairly closely.

Based on the -3 db point the thermal time constant is 610 μs. This same unit was measured to have a time constant of 685 μs from cooling curve exponential decay data.

Measuring the phase shift in the thermal follow by the technique described in the previous paragraphs there is a fairly linear relationship between $\tan\beta$ and ω (Figure 6) indicating that the time constant is independent of frequency. For data taken at five frequencies the average time constant comes out as 601 μs. This is in good agreement with the third harmonic response data.

The third harmonic amplitude function was checked out for another unit at a fixed frequency of 60 cps. This data is shown in Figure 7 as a plot of third harmonic voltage vs $I^3_{rms}R^2$. If α and γ are assumed constant then a linear relationship should exist. The plot demonstrates this. Actually the bridgewire resistance varied from 2.75 ohms at 10 ma current to 3.32 ohms at 50 ma. It was observed that the time constant varied by 10% (increased) during this current range in which the power dissipation varied by a factor of 25. Previous tests have indicated that time constant can vary with power level.

Since the harmonics generated depend on the cube of current, a small variation in current will reduce the useful signal significantly. The current must be at a safe level if the device under test is loaded. Some typical waveforms observed are shown in Figure 8. At the top, the error waveform contains a distinct fundamental which can be cancelled out by the resistance (R_x) and reactance (C_x) balance to yield an essentially pure third harmonic. At balance all amplitudes are equal. As a phase display the center trace contains a fundamental component resulting in an opened type of Lissajous figure. A phase shift will produce the same general type of display. Only at balance will the single cubic trace shown at the bottom appear.

The fixed frequency bridge of Figure 2 provides a rapid measurement. After the current is set to the desired level, the bridge is balanced by means of R_x and C_x. The third harmonic output is noted and the error is displayed as a phase pattern. By adjusting the phase shift network, the phase is balanced to provide a single cubic trace as previously described. From the phase reading, Figures 3 and 4 are employed to give the time constant τ and $\tan\beta$. Now going back to equation (5), and introducing the transformer step up ratio of 19.25 the value of γ is determined according to

$$\gamma = \frac{I^3_{rms}R^2\alpha}{2V_{3\,rms}} \times 19.25 \times \frac{1}{\sqrt{1+\tan^2\beta}} \qquad (7)$$

The temperature coefficient of resistivity α must be known or determined from some other procedure. Note that multiplying the observed third harmonic by the factor $\sqrt{1+\tan^2\beta}$ corrects the amplitude back to the complete follow region. The resistance is known from the reading R_x.

A series of measurements were made on a bridgewire to demonstrate the influence of environment on the thermal parameters. The same unit was used in all measurements at a current level of 50ma.

Environment	Resistance, R ohms	Time Constant, τ m sec	Heat Loss Factor, γ uw/°C
Air	4.25	4.2	70
Ethyl Acetate	4.15	1.6	318
Water	4.11	0.98	1220
Lacquer (Dry)	4.11	0.73	1270

The environment acting as a heat sink increases the heat loss factor and reduces the thermal time constant. Note also that as the heat sink increases, with the corresponding increase in γ, the lower the average temperature and therefore the lower the hot-resistance value, R. However the additional mass surrounding the wire has also increased the effective heat capacity. If an explosive mixture were to surround the wire, the intimacy of contact would similarly reflect in the change of thermal parameters.

The type of measurement possible has been indicated. The usefulness of the measurement will depend on whether electro-explosive device performance can be related. This bridge method appears to offer a quick and reliable measurement technique.

CONCLUSIONS

The measurement of the thermal time constant and the heat loss factor of a bridgewire from the amplitude and phase shift of the third harmonic generated in it by a sinusoidal current has been shown feasible. The theory and mathematics have been presented and an electronic instrument which was built for the measurements has been described and detailed. The new instrument greatly accelerates the measurements of the thermal time constant and the heat loss factor. The instrument will be particularly useful for making measurements on EEDs containing bridgewires of very low thermal coefficients of resistivity, such as tophet -C. The measurements made with the new instrument show the results to be in good accord with the theory and mathematics, and in addition indicate that in general the thermal characteristics of a bridgewire can be described by the constants of the simple power balance differential equation:

$$C_p \frac{d\theta}{dt} + \gamma\theta = P(t)$$

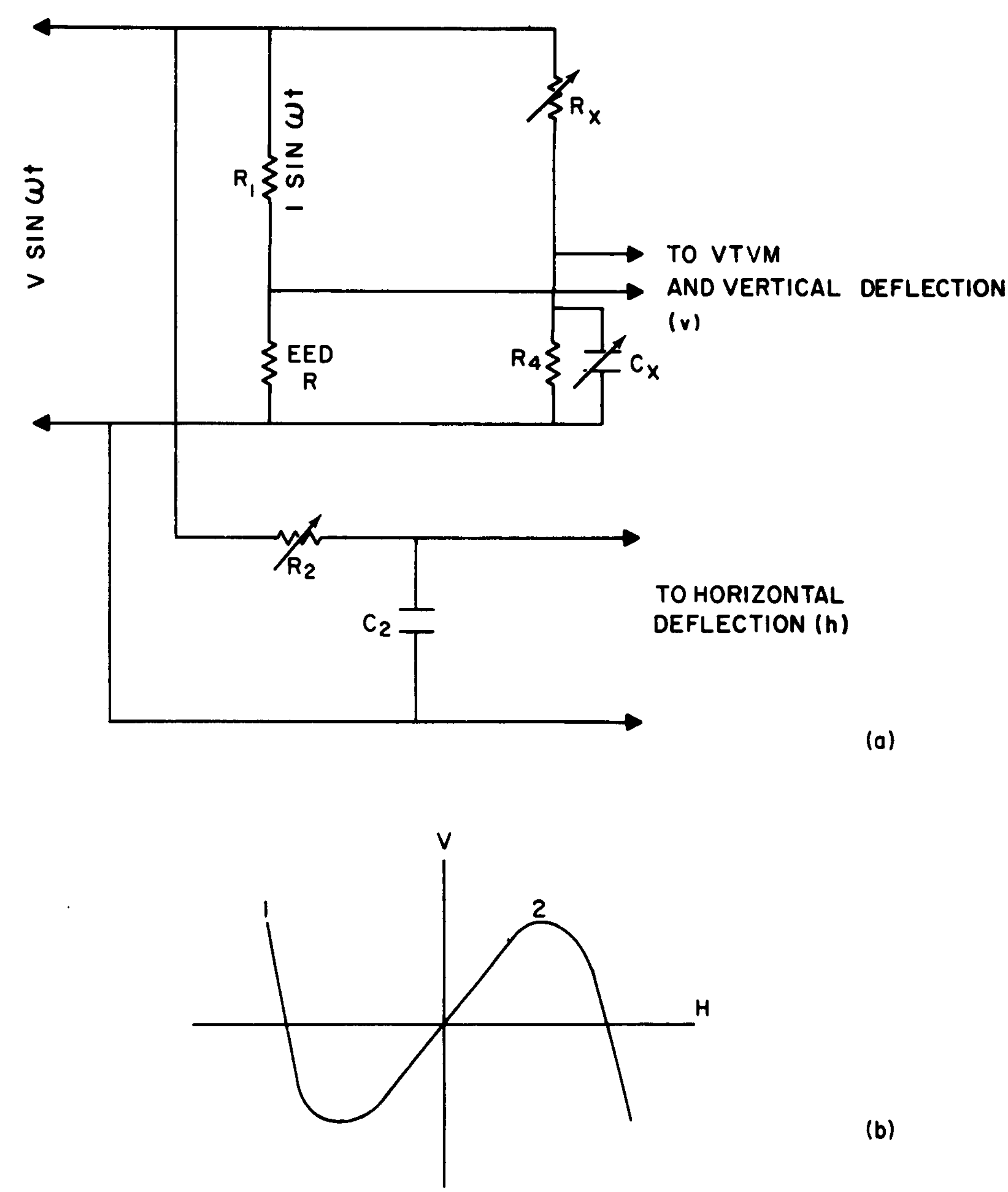


FIG.1 (a) THE BASIC NONLINEAR BRIDGE CIRCUIT. (b) THE PHASE DISPLAY WAVEFORM AT BALANCE.

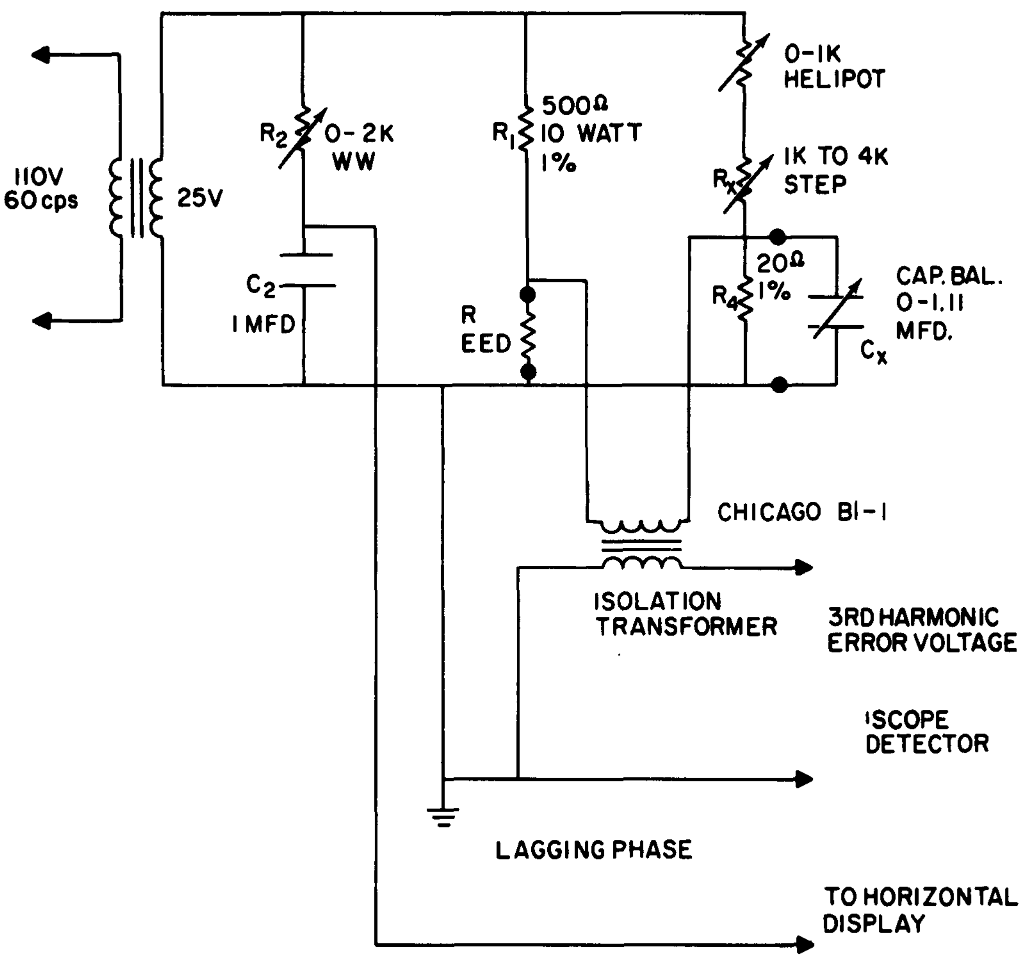


FIG. 2 THE COMPLETE SELF CONTAINED BRIDGE
CIRCUIT WITH COMPONENT VALUES
(LINE FREQUENCY (60 cps))

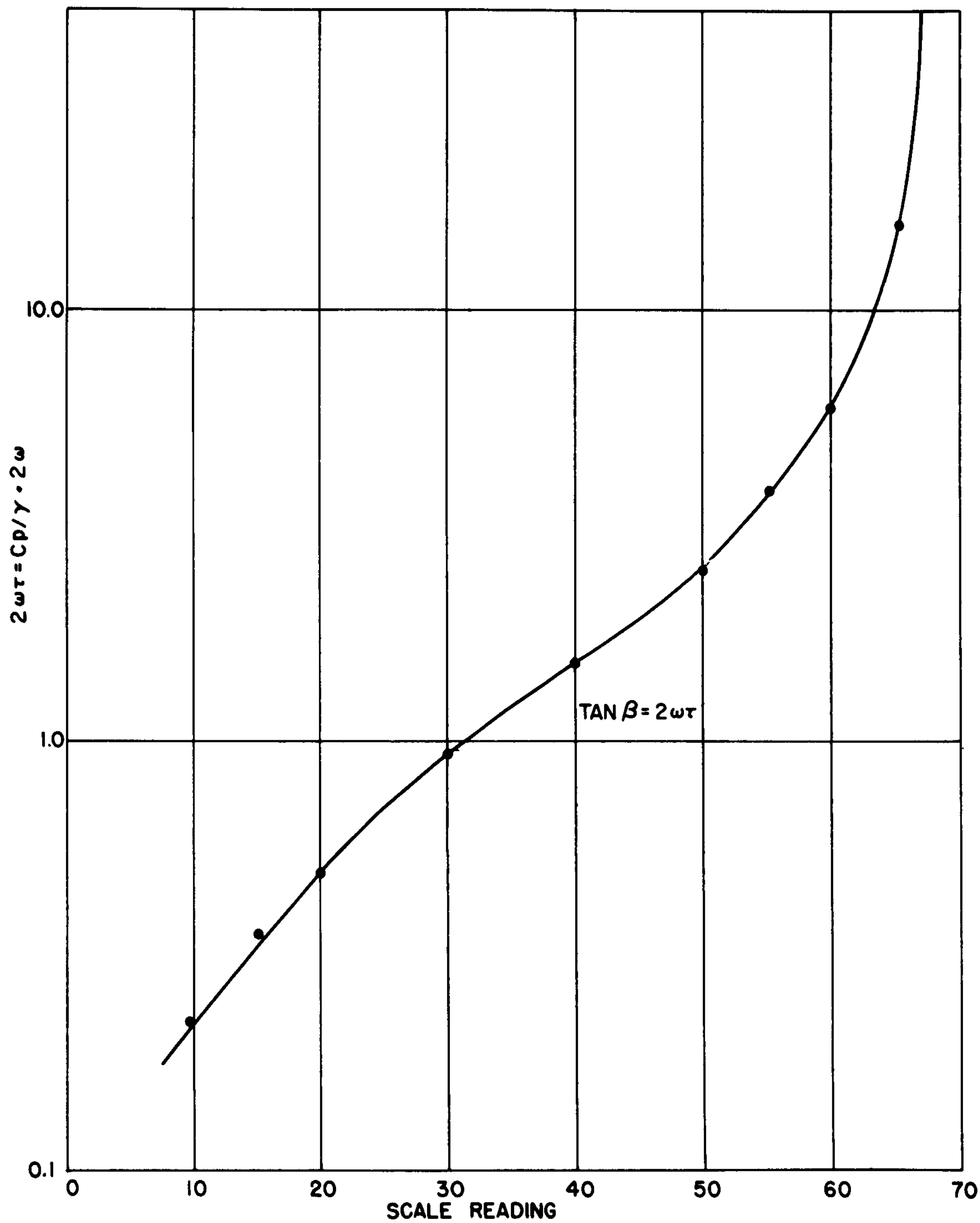


FIG. 3 THE BASIC SHIFT CALIBRATION CURVE

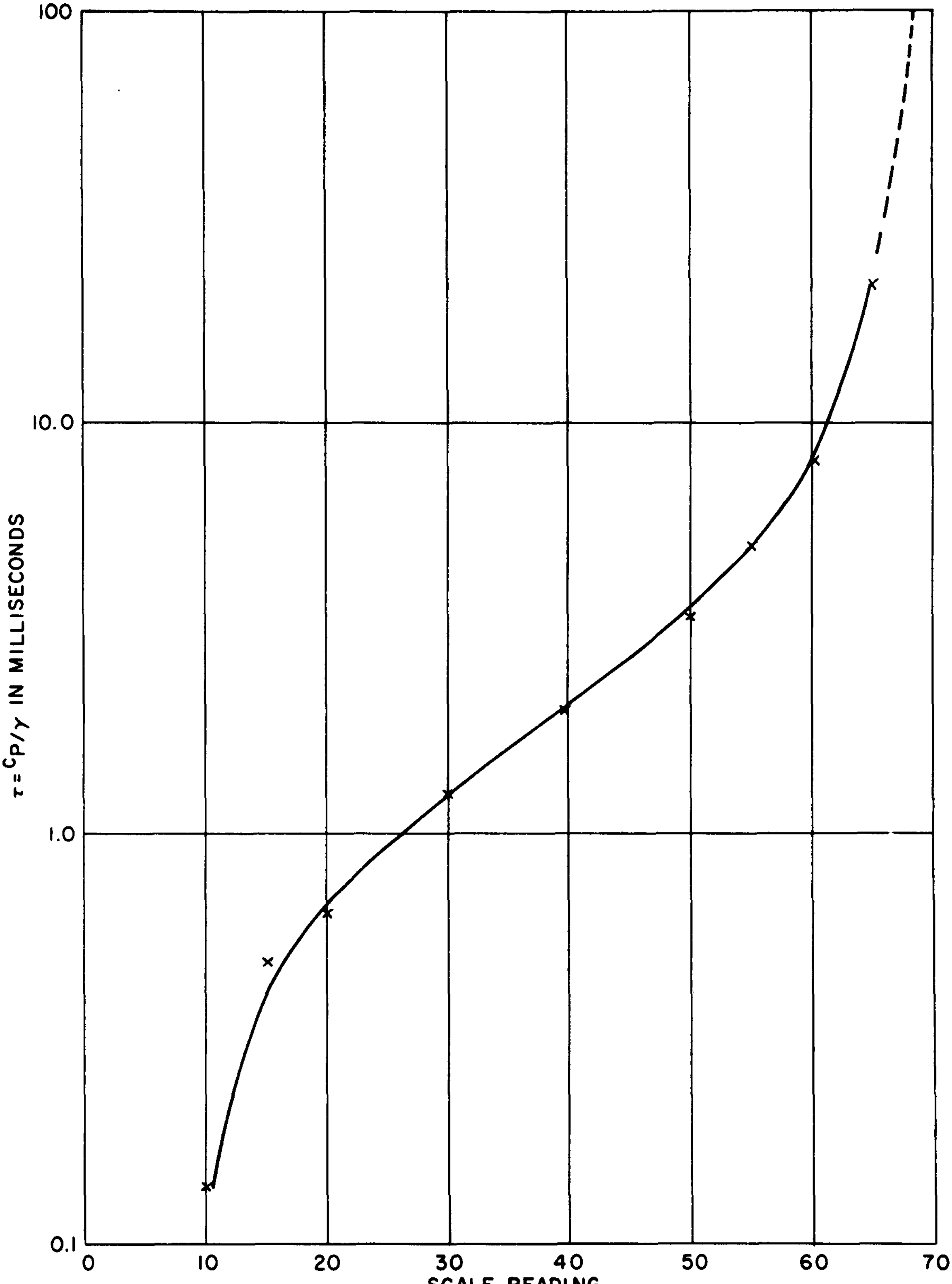


FIG. 4 THE CALIBRATION OF THE PHASE SHIFT NETWORK TO PROVIDE THE TIME CONSTANT τ DIRECTLY

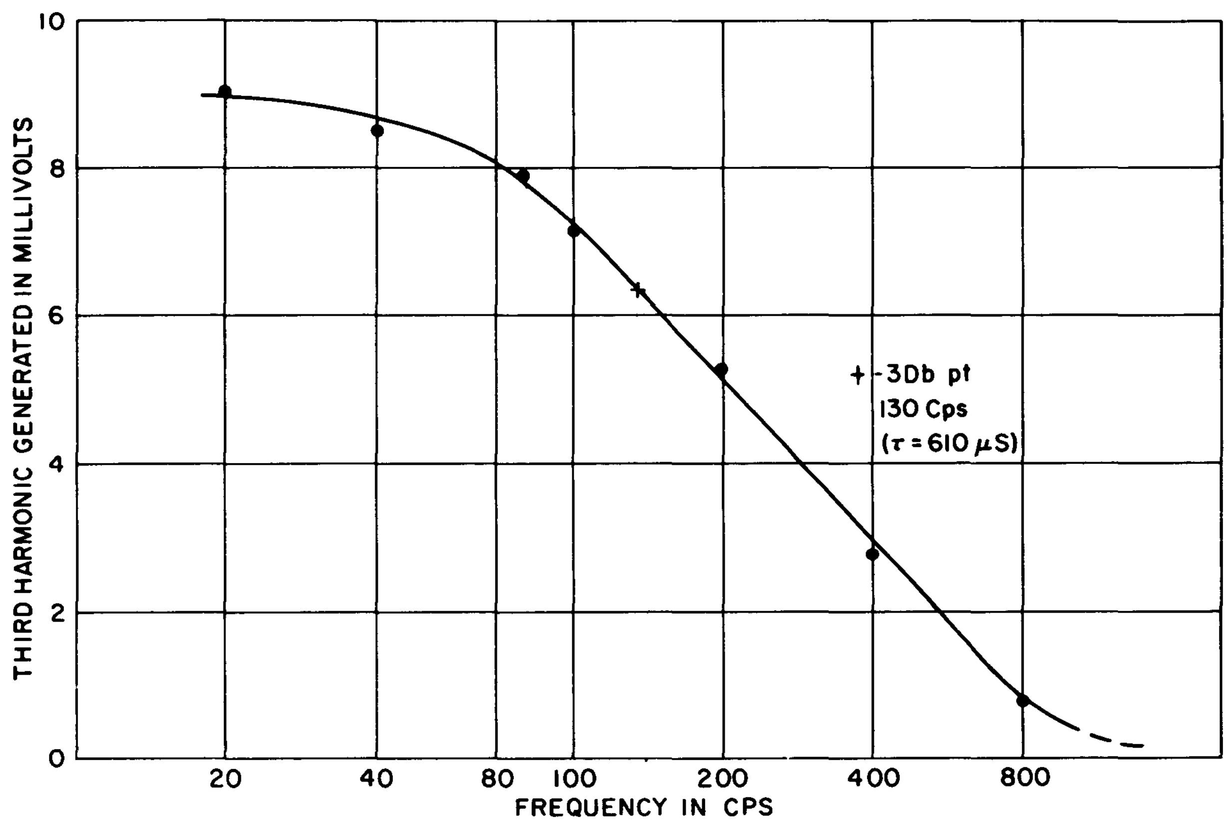


FIG. 5 THE THIRD HARMONIC ERROR VOLTAGE AT BALANCE AS A FUNCTION OF LINE FREQUENCY

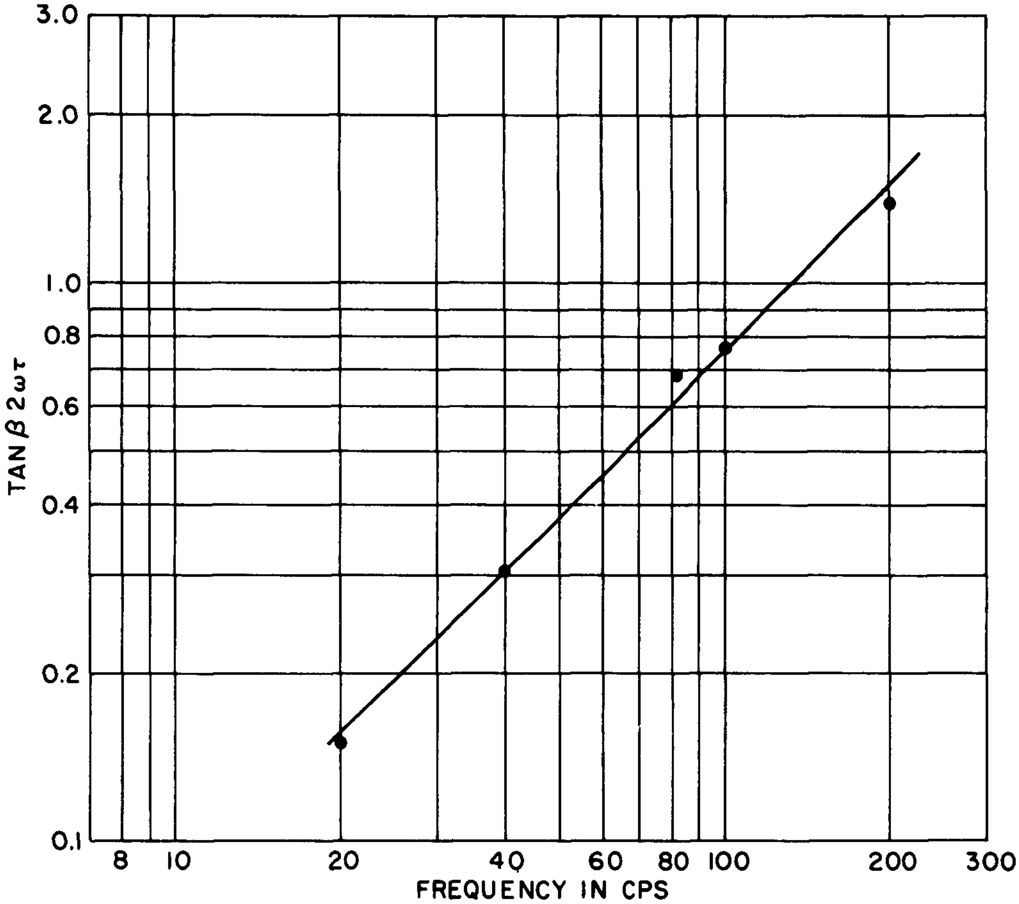


FIG. 6 DEPENDENCE OF TAN β ON FREQUENCY

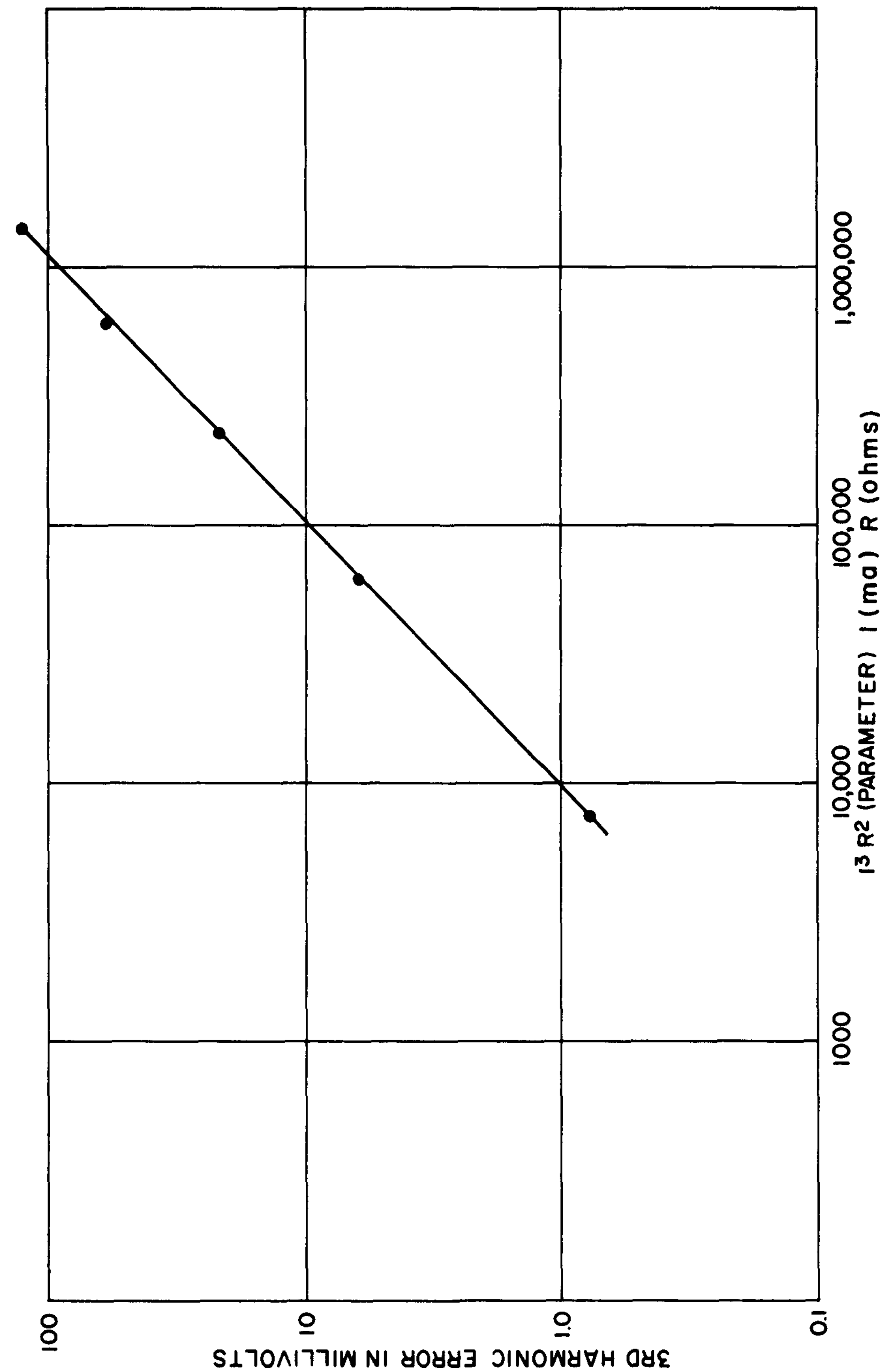
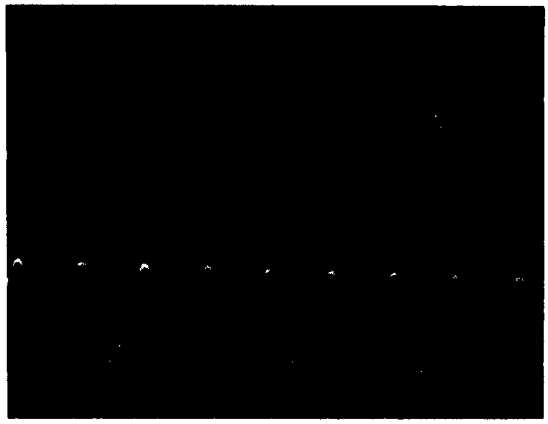
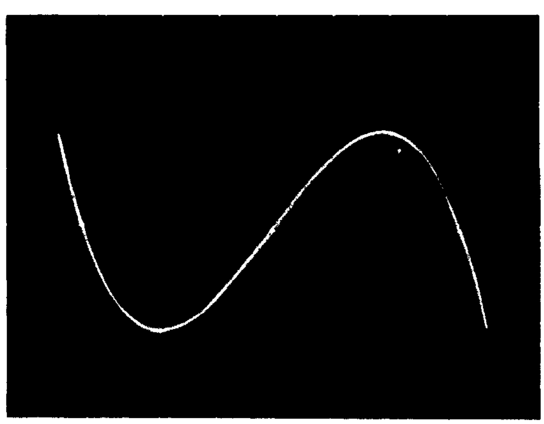


FIG.7 THE THIRD HARMONIC AMPLITUDE VS THE PARAMETER $I^3 R^2$



ERROR SIGNAL AND THE RESIDUAL THIRD HARMONIC

LISSAJOUS PHASE DISPLAY WITH PHASE SHIFT



TRACE AT BALANCE

FIG. 8 TYPICAL ERROR WAVEFORMS

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	DESCRIPTORS	CODES		DESCRIPTORS	CODES
SOURCE	NOL technical report	NOLTR	SECURITY CLASSIFICATION AND CODE COUNT	Unclassified - 33	UØ33
REPORT NUMBER	62-205	62Ø2Ø5	CIRCULATION LIMITATION		
REPORT DATE	5 March 1963	Ø363	CIRCULATION LIMITATION OR BIBLIOGRAPHIC		
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SUBJECT ANALYSIS OF REPORT

DESCRIPTORS	CODES	DESCRIPTORS	CODES	DESCRIPTORS	CODES
Measuring	MEAU	Low temperature	LOWM	Amplitude	AMPI
Electrothermal	ELTH	Temperature	TEMP	Time	TIME
Bridge	BRID	Equation	EQUA	Constant	COSA
Wires (Characteristics)	WIREC	Follow	FOLL	Heat	HEAT
Nonlinear	NONI	Wire	WIRE	Loss	LOSS
Thermal	THER	Harmonic	HARM	Factor	FACR
Parameters	PARA	Voltage	VOLT	Alternating current	ALTE
Instrumentation	INSM	Drop	DROP	Angle	ANGL
Electro-explosive	ELEX	Sinusoidal	SNEZ	Explosives	EXPL
Devices	DEVI	Current	CURR		
Low	LOWE	Phase	PHAE		
Coefficients	COEF	Lag	LAGG		

Naval Ordnance Laboratory, White Oak, Md.
(NOL technical report 62-205)
NONLINEAR BRIDGE FOR MEASURING ELECTROTHERMAL CHARACTERISTICS OF BRIDGEWIRES (U), by Louis A. Rosenthal. 5 March 1963. 8p. diagr. Task NOL 443. UNCLASSIFIED

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Abstract card is unclassified.

1. Electro-explosive devices
2. Wires, Bridge - Thermal properties
I. Title
II. Rosenthal, Louis A.
III. Project

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